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Probabilistic analysis of marine fuels in emission controlled areas

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Abstract

This study presents a probabilistic analysis for conventional diesel-fuelled engines, LNG-fuelled engines or dual-fuelled (LNG and diesel) engines to establish which is more optimal for container shipping within emission controlled areas. Variables investigated include uncertainty over future NO_x and EE regulations, downtime due to engine failure, limitations to LNG bunkering and fuel prices. Decision analysis given perfect information and risk analysis were used to generate varying scenarios to understand how the optimal decision was affected. The optimal decision for a risk neutral decision maker is to invest in a diesel fuelled engine. With perfect information over future NO_x regulations, the optimal decision changes to that of purchasing a LNG-fuelled engine. The model also highlights the importance of risk tolerance to the decision problem. On the whole, the more risk averse decision makers are, the likelier they would consider LNG as an alternative fuel source.

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IMO regulations; decision analysis; LNG; shipping

1. Introduction

The International Maritime Organisation (IMO) introduced mandatory regulations to reduce the sulfur content in fuels to 0.10 per cent for all ships that pass through emissions control areas (ECAs). This regulation will be effective from January 2015 [1], and may be followed by regulations to reduce nitrogen oxide (NO_x) for all ships built after 2016 [2]. As ship owners explore various fuel alternatives to meet international standards, this paper examines how the uncertainty over various system variables such as future liquefied natural gas (LNG) bunkering infrastructure, regulations and fuel prices affects decision makers' selection of marine fuels for their ship operations. DPL Decision Tree software was used to provide a probabilistic analysis and optimal decision policy.

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2. Methodology

In this study we analysed mid-sized containerships ploughing between Europe and Asia, more specifically the LP1-Asia Europe Loop 1[3]. A *purchase decision* between three types of ship engines was considered. They include a typical two stroke diesel fuelled engine fitted with sulfur oxide (SO_x) scrubbers, a gas fired engine that allows LNG as a fuel source and a dual fuel engine that allows a combination of LNG and fuel oil. Decision specifications such as cost of buying the three engines, cost of operating SO_x scrubbers, and revenue earned were estimated from publicly available sources [4]–[6]. Other specifications such average loading and unloading at each port, number of voyages per week and speed of ship were estimated based on a mid-sized containership traveling between Europe and Asia.

The first system variable *I* ($), is additional costs that would be incurred given the uncertainty over future NO_x and energy efficiency (EE) regulations that would be realised by 2016 [2]. Since we assume that it is imperative for the ship operator to operate within ECAs, the outcome of future regulations would have a direct impact on the net present value (NPV) of purchasing a diesel fueled engine. However the level of NO_x emissions also depends on other environmental parameters such as pressure, humidity and air temperature that is not considered, making this analysis useful only for a preliminary assessment in propulsion design.

The next system variable considered was the reliability of different engine types. It should be noted that the reliability of an engine is affected by a wide variety of factors. A detailed technical and operational analysis would be required to accurately model the reliability of various engine types. However using downtime *d* (weeks), due to engine failures, reliability can be sufficiently represented. Since downtime has a varying effect on the three decision alternatives, it is denoted by d_1, d_2 and d_3. The third and fourth variable represents the price of diesel P_{dies} ($/mmBTU) and the price of LNG P_{lng} ($/mmBTU) respectively. Distillates such as marine gas oil (MGO) is designed for use in all diesel-fuelled engines. It also has an extra low sulfur content making it a suitable choice for representing P_{dies} [7]. It should be noted that for ships that travel to ECAs less frequently, fuel switches between heavy fuel oil and MGO should be considered in the analysis. Lastly to evaluate how limitations in LNG bunkering infrastructure may affect the decision outcome, distance travelled per year *D* (km) was considered. Within the boundaries of our problem, the distance travelled would not vary much for diesel and dual fuelled engines. However if only a few ports provide LNG bunkering services, an LNG fuelled ship would have to travel an additional distance to carry out refueling. Thus distance travelled per year for LNG fuelled ships faces a certain level of uncertainty. In general, for all three decision alternatives, the NPVs are of the following form:

$$\mathrm{NPV}_{1,2\text{ or }3} = \text{Initial costs} + \sum_{k=3}^{7} \frac{(\text{Earnings})}{(1+i)^k} - \sum_{k=3}^{7} \frac{(\text{fuel costs})}{(1+i)^k} \tag{1}$$

where *k* represents the year (i.e. year 2016 is represented by $k = 3$) and *i* represents the discount rate. $NPV_{1,\ 2\text{ or }3}$ represents the value of purchasing a diesel fueled, LNG fueled or dual fueled engine respectively. For $NPV_{1,}$ initial costs include additional costs due to uncertainty in regulations. For NPV_1 and NPV_3, a constant value of 183, 690 km was assumed for distance travelled per year, *D*. Also for calculation of annual earnings in NPV_2 and NPV_3 a factor of 0.97 is applied to factor in a reduced container space due to the presence of LNG fuel tanks [4]. And finally for all three decision alternatives it is assumed that the ship makes four round trips per year which is the equivalent of 48 weeks.

A probabilistic assessment of each system variable was carried out using publicly available data. In other cases, discussions with former consultants and maritime staff provided a useful indication for certain system variables. Table 2-1 provides the summary of the probabilistic assessment carried out for each variable. Values and probabilities presented are only estimates at best, however a sensitivity analysis on both the values and probabilities reveals that small changes to these values and probabilities does not affect the optimal decision.

Table 2-1 Probabilistic assessment of system variables

Discrete Chance Variable	Probability (value)			
Downtime, $d_{1,2,3}$ [1]	*High outcome*		*Base outcome*	*Low outcome*
d_1 for diesel	0.01 (8)		0.09 (1.25)	0.9 (0)
d_2 for LNG	0.02 (8)		0.08 (1.25)	0.9 (0)
d_3 for dual fuel	0.04 (8)		0.06 (1.25)	0.9 (0)
Additional distance traveled, D [2]	*'Yes' outcome*		*'No' outcome*	
D	0.92 (275, 534 km)		0.08 (183, 690 km)	
Additional costs incurred, I [3]	*NOx and EE*	*NOx only*	*EE only*	*None*
I	0.4(10.53)	0.4(10.03)	0.1(2.76)	0.1(0)
Prices, $P_{dies,\ lng}$ [4]	*High outcome*		*Base outcome*	*Low outcome*
P_{dies}	17% (26.5)		67% (17.9)	17% (9.3)
P_{lng}	17% (20.7)		67% (16.5)	17% (12.4)

[1] Values and probabilities derived from [8], [9] and interviews with former maritime staff.
[2] Derived from [10]. 'Yes' represents additional distance traveled by LNG fueled ships due to limitations in existing infrastructure and 'No' represents the base value distance traveled by ships due to sufficient LNG bunkering infrastructure.
[3] Exhaust gas recirculation (EGR) technology was used to approximate the costs incurred for retrofitting NO_x removers from [11], [12]. 12 and 3 weeks of downtime were assumed respectively for implementing NO_x and EE regulations. Probability of additional costs was estimated from various IMO and MEPC documents [13], [14].
[4] DPL software was utilised to perform moments matching to find the discrete values and probabilities for the three outcomes for P_{dies} [4] to estimate P_{dies}. P_{lng} values are the average of European and Asian LNG price forecasts. Values and probabilities are based on [10]. For decision alternative 3, joint probability distributions of P_{dies} and P_{lng} were utilised

3. Key results

A deterministic analysis, using base outcome values, showed that the optimal decision was to choose an LNG-fuelled engine. On the other hand, a probabilistic analysis revealed that the optimal decision changes to purchase a diesel-fuelled engine for a risk neutral decision maker. This highlights that the decision to switch to cleaner fuel options is strongly influenced by probabilistic events.

Scenario analysis was conducted assuming perfect information of prices, limitations to LNG bunkering and future regulations (see Table 3-1). From the table we can deduce that so long as LNG prices are cheaper than diesel prices, using LNG as a fuel source turns out to be the optimal decision. In the event of high diesel and LNG prices, the use of LNG as a fuel source can still be expected since dual fuel engines becomes a more optimal decision. Secondly, improving LNG bunkering infrastructure does help to promote LNG being used as a fuel source. In addition, given perfect information over future regulations to reduce NO_x, the optimal decision for ship owners would be to invest in an LNG-fuelled engine.

Table 3-1. Summary of optimal decision pathways given perfect information over various system variables

Price of diesel	Price of LNG	Optimal decision
High	Low/Base	LNG
Base	Low	LNG
High	High	Dual
All other variations		Diesel
Limitations in LNG bunkering infrastrucutre		Optimal decsion
High		Diesel
Low		LNG
Future regulations in 2016		Optimal decision
NOx only or with EE regulations		LNG
Only EE regulations or none		Diesel

A risk analysis was also carried out, assuming the decision maker has an exponential utility function and satisfies the delta property [15]. With decreasing risk tolerance (increasing risk aversion) the optimal decision changes from diesel to LNG and finally to dual fuel engines. This tends to seem counterintuitive, given that dual fuel engines are often considered to be the 'more risky' option. However, it should be noted that while some factors make dual fuel engines more risky such as downtime due to engine failures, other factors tend to make it less risky such as less uncertainty over future regulations and fuel prices.

4. Conclusion

In conclusion, this study finds that the optimal decision for a risk neutral decision maker is to invest in a diesel fuelled engine. Price uncertainties have a much larger impact on the optimal decision than other uncertainties such as engine failures and downtime. Nonetheless, in the event of perfect information over future regulations, the optimal decision shifts to that of purchasing a LNG-fuelled engine. The study also shares that improving LNG bunkering infrastructure does make LNG-fuelled engines a more viable option, and potentially imposing price regulations on diesel to make LNG more attractive could improve the adoption of LNG fueled engines. The model further suggests that investing in a dual-fuelled engine in most cases is a sub-optimal decision due to higher costs. Finally, this study also highlights the importance of risk tolerance to the investment decision. On the whole, the more risk averse decision makers are, the more likely they would consider LNG as an alternative fuel source.

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Biography

Kamal Soundararajan is from the Energy Studies Institute (NUS). His main area of research at ESI centres on energy efficiency studies, with a focus on the maritime sector and large scale industrial systems. Kamal is also studying behavioral issues related to energ efficiency investments and has been actively involved in energy performance and benchmarking studies since October 2012.